TEMPORAL TRENDS OF ENERGY CONSUMPTION AND CO_2 EMISSIONS IN RIYADH, SAUDI ARABIA

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ABSTRACT
The consumption of material, energy, and water resources is inextricably linked to population growth with a unique impact on urban areas, especially in light of significant investments in infrastructure to support urban development. Urban metabolism is becoming popular as it provides a framework accounting the mass and energy flows through a city. An urban metabolism study was conducted to estimate the inputs and outputs of energy and pollutants from Riyadh, Saudi Arabia. The objective of this study was to determine the energy consumption of Riyadh using locally generated data from 1986, 1996, 2006, and 2012 and analysing the temporal trends of energy consumption and associated environmental impact. The socioeconomic and biophysical characteristics of Riyadh are well represented in its metabolism indicators. The high growth rate in population along with urban expansion has resulted in an increase in energy consumption. Riyadh has seen an increase in energy consumption at a rate of about 6% per annum. On a per capita basis, preliminary results show that the energy consumption increased by 31% from 1996 to 2012. Also, per capita CO_2 emissions have increased by the same percentage. Results also show increasing mobile energy consumption from 20k TJ in 1986 to 157k TJ in 2012, which points to Riyadh's inefficient urban form. The study findings highlight the importance for developing effective policies for improving the use of resources
Keywords: resource consumption, sustainability, urban development, urban metabolism..

1 INTRODUCTION

In 2014, 54% of the global population resided in urban areas; this percentage is expected to reach 66% by 2050 [1]. Not only do cities currently have a higher population than in the past, but the typical resident of modern cities is also likely to consume more resources, the average person living in a rural area' instead of 'the average out-of-city person [2]. Managing urban growth is a key challenge of the twentyfirst century [3]. Rapid urban growth is usually associated with tremendous challenges, including increases in materials and energy flows that enter and exit urban systems [2]. This has placed considerable pressure on urban societies to adopt sustainability as the main mechanism for development.

Urban metabolism (UM) has become an important assessment tool for the analysis of urban systems. It quantifies the overall fluxes of energy, water, material, and wastes into and out of urban regions [4]. Improving the understanding of these flows within cities would result in better approaches towards developing more sustainable cities. UM was developed to help quantify and assess urban environmental loads, for example [2, 5].

UM analysis is defined as a promising form of assessment, as it provides the annual sum of material and energy inputs and associated emissions [6]. Kennedy defines UM as 'the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste' [2]. Chester *et al*. (2012) define UM as the dominant framework for evaluating the products, accumulation of resources and wastes expelled by cities [7].

The increasing urbanization of today's societies, along with the intense energy demands, has driven the recognition that sustainable practices need a systems approach to both the application and study of sustainability principles [8]. When applied to the analysis of resource consumption

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in cities, UM can provide important indicators, especially when coupled with socioeconomic indicators [9]. In this type of analysis, however, understanding the time series data is a crucial factor in the development of sustainable polices, particularly when the objective is to reduce the impact of the system.

The objective of this study is to determine the energy flows and associated impacts on Riyadh, Saudi Arabia, using UM, drawing on data from 1986, 1996, 2005, and 2012, and analysing the temporal trends in resource consumption and associated environmental impacts.

2 CASE STUDY

Riyadh has the largest population among cities in the Arabian Peninsula. The population of Riyadh has grown from almost one million in 1980 to nearly six million today and is expected to reach 8.2 million by 2029 [10]. Between 2004 and 2010, the population of Riyadh grew at a rate of 4% annually. The increase in population is still the most noticeable feature of Riyadh and this in turn has led to the growth of other sectors. In the last year, the overall population of Riyadh reached 6,152,180 [10]. However, Riyadh's population growth is characterized by qualitative improvements in its residents' standard of living [10].

As the capital of the Kingdom, Riyadh City has witnessed growth rates higher than that of other cities. This strength in its economy can be explained by the increasing population and the consequent job opportunities that sustain the growth in demand for services and goods, in addition to its location at the centre of a large regional market represented by the Gulf Cooperation Council (GCC) states and other neighbouring countries [10].

Within a mere half a century, Riyadh City transformed from a small village surrounded by walls into a modern city. The first developed area covered about 632 sq. km, the second about 1.150 sq km, and the recently developed area covers 950 sq. km. This expansion has resulted in Riyadh becoming the largest metropolitan area in the country. There are 948,554 households in Riyadh, with an average size of 6.2 individuals per household. This average is expected to fall to about 5.9 individuals per family in 2024 [10]. The majority of Riyadh's population (64.7%) is aged between 15 and 59 and the labour force comprises about 52% of the population [10].

Riyadh's electrical energy is drawn from a combination of sources: 54% oil and 46% natural gas [11]. This type of fossil-based electricity generation has led the energy sector to become the major source of CO_2 emissions in the Kingdom [12]. Potable water is delivered to Riyadh from two main sources. The first 60% of the supply, is from desalinated seawater, which comes from desalination plants in Jubail on the Arabian Gulf through special pipes. The second source is from local artesian wells, which comprise 40% of the total water supply [10].

3 METHODOLOGY

The objective of this study is to determine the energy flows of Riyadh, Saudi Arabia, using UM, drawing on data from 1986, 1996, 2005, and 2012, and analysing the trends in resource consumption and material flows. These years were chosen as the target years, because the largest amount of data was available for this period. To facilitate the collection of data on the UM of Riyadh, this study adopted a standardized indicator set developed by Kennedy *et al*. (2014) [9]. The data was organized into four categories: biophysical (land use); socio-economic (population, economy); UM (consumption of energy, electricity sources, water consumption, solid waste, wastewater, and emissions); and quality of life indicators (transport modes, automobile ownership). The main data sources were reports from

Arriyadh Development Authority (ADA), including the Metropolitan Development Strategy for Arriyadh (MEDSTAR) and the Investment Plan for Riyadh reports. Other sources included the National Water Company, the Saudi Electricity Company, the Municipality of Riyadh, the Electricity and Cogeneration Regulatory Authority (ECRA), and the Saudi Aramco Annual Review reports. Table 1 shows the methods and procedures used to conduct Riyadh's UM study. It shows the data collection as well.

Table 1: Selected indictors and data sources.

Urban indictors	Data collection approach	Category	Data sources
Energy (stationary)	Using locally generated data	Input flows	Arriyadh Development Authority (ADA)
Energy (mobile)	Multiplication of the within-boundary vehicle kilometres travelled (VKT) by the fuel economy (L/km) for each vehicle grouping	Input flows	Vehicle kilometres travelled data and vehicle grouping from ADA estimates Fuel economy (L/km) based on average data. www.rita.dot.gov
Water consumption	Using locally generated data	Input flows	National Water Company
Materials	1. Classifying of each group then needs to be established with the help of local architects and engineers who have bills of buildings and other infrastructure into representative groups with typical material characteristics. 2. Collecting data on the annual additions, demolitions, and stocks of each group. 3. Statistically representative quantities for the material components quantities from projects completed in the city.	Input flows	Riyadh municipality and ADA reports
Emissions from energy (stationary)	Using emission factors as reported by the National Committee for the Clean Development Mechanism. www.cdmdna.gov.sa	Output flows	National Committee for the Clean Development Mechanism. www.cdmdna.gov.sa
Emissions from energy (mobile)	Using default values reported by IPCC under chapter 3 (Mobile Energy) [15]	Output flows	The Intergovernmental Panel on Climate Change (IPCC)
Wastewater	Using locally generated data	Output flows	Data obtained from National Water Company

3.1 Inputs to the Riyadh ecosystem

Preliminary estimates of inflows of energy (stationary/mobile) and water to Riyadh are provided in the following categories. Each category describes the methodology used to obtain the data.

3.1.1 Energy flows

Energy consumption in Riyadh is divided into stationary uses and mobile uses. In stationary cases, energy use is reported first by the type of source, and second by the type of user. Local data were used to estimate stationary energy consumption. On one hand, mobile energy use was reported by the type of fuel. For this study, data pertaining to vehicle kilometers travelled (VKT) were obtained from the Arriyadh Development Authority (ADA). These data were reported based on each vehicle grouping. Average fuel economy was then multiplied by (VKT) for each grouping to quantify transportation fuel use in Riyadh.

3.1.2 Material flows

Construction materials constitute the largest stocks and flows of materials for cities. However, quantifying the stocks and flows of construction materials for cities, such as aggregates, cement, glass, steel, and wood, is challenging. This study adapted a bottom–up approach to estimate the materials flow in Riyadh. This approach involves a process of classifying the buildings and other types of structure in a city and making representative groups with the typical material characteristics. The quantities of the material components for each group represented were then established using bills supplied by local firms engaged in projects that have been completed in the city. However, this portion of the research is ongoing and detailed results will be reported in a subsequent paper.

3.1.3 Water flows

Due to the large amount of water flowing through cities, understanding the role of water in establishing balance is critical; this is especially true for cities in a hot and arid climate. Data pertaining to water production, water sources, and water consumption were obtained from ADA reports in MEDSTAR.

3.2 Outputs from the Riyadh ecosystem

Data on residential and commercial solid waste were obtained from the Riyadh municipality and from the ADA in MEDSTAR reports. Locally generated data from the National Committee for the Clean Development Mechanism was used to estimate CO_2 emissions. Emissions from road transportation were estimated following IPCC methodology [15].

The CO_2 emissions associated with energy consumption are calculated using the Saudi Arabia electricity mix ratio (45% natural gas, 55% oil) as reported in ECRA [13].

4 RESULTS

Preliminary results are provided in the following categories. Each category describes the methodology used to obtain the data. Flows of construction materials are not reported, as this part of the research is ongoing.

4.1 Socioeconomic indicators

Since the 1970s, the growth rate of the city's population has never been less than 4.5%. Results also show that Riyadh's GDP per capita has increased significantly by more than 200%. This may be explained by the rise of oil price during the last several years. Table 2 summarizes the socioeconomic indicators for Riyadh.

4.2 Biophysical indicators

Results show that developed land areas in Riyadh is growing annually at a phenomenal rate of about 6%. The most unique feature in the biophysical indicators of Riyadh is the fact that the majority of lands within the city limits are specified as undeveloped. In recent attempts to tackle this issue, the government of Saudi Arabia is planning to impose a land tax to discourage urban land owners from keeping these lands vacant. Table 3 summarizes the biophysical indicators for Riyadh.

4.3 Urban metabolism indicators

The socioeconomic and biophysical characteristics of Riyadh are well represented in its metabolism indicators. As shown in Table 4, Riyadh has seen an increase in energy and water consumption at a rate of about 6% and 4% per annum, respectively. This can be explained by the high growth rate in population along with urban expansion.

Table 2: Socioeconomic indicators for Riyadh.

Socioeconomic indicators	1986	1996	2005	2012
Population	1,389,500	3,004,600	4,138,329	5,676,621
Density	2220/km^2	1950/km^2	2167/km^2	2379/km^2
Household size	6.3	6.4	6.2	6.2
Manpower	423,918	716,000	1,300,000	2,350,000
Unemployment	5%	18.4%	12%	7%
Average annual income (USD)	$8,985	$9,187	$14,069	$ 24,912
GDP per capita (USD)	$8,634	$4,726	$4,832	$14,445

Table 3: Biophysical indicators for Riyadh.

Biophysical indicators	1986	1996	2005	2012
Land area total (km^2)	632	1149	1782	1910
Developed land area (km^2)	235	381	577	816
Undeveloped land area (km^2)	329	1122	1205	1094
Residential building gross floor areas (millions m^2)	83	160	181	219
Commercial building gross floor areas (millions m^2)	11	25	26	57

Table 4: Urban metabolism indicators.

Urban metabolism indicators	Note	1986	1996	2005	2012
Energy (stationary)	Total (GWh)	9,552	16,600	26,900	41,270
	Residential	60%	60%	57%	52%
	Commercial	8%	8%	12%	17%
	Industrial	3.2%	6%	7%	8%
	Institutional	24%	24%	19%	18%
	others	4.8%	2%	5%	5%
Electrical line losses		10%	10%	10%	9%
Energy mobile (TJ)	Gasoline	20,012	61,384	135,166	157,276
	Diesel	5,761	12,926	24,268	47,799
	Jet Fuel	---	---	21,119	28,456
Water consumption	Millions m^3/day	0.776	1,.3	1.7	2.1
Water line losses		17%	15%	17%	17.5%
Water Production Sources	Ground	35.5%	35.5%	40%	40%
	Desalination	64.5%	64.5%	60%	60%
Wastewater volume	Thousands m^3/day	361	453	600	923
Solid Waste	Millions of tons	2.6	5.7	8.3	14.1
	Tons/capita	1.9	1.9	2	2.4

4.4 CO_2 emissions

4.4.1 Energy stationary

The CO_2 emissions associated with energy consumption are calculated using the Saudi Arabia electricity mix ratio (45% natural gas, 55% oil) as reported in ECRA [13]. Emissions factors for electricity production reported in [14] are used to calculate the total CO_2 emissions of energy consumption.

4.4.2 Energy mobile

The CO_2 emissions associated with the transportation sector are calculated following the procedures reported in the IPCC Guidelines for National Greenhouse Gas Inventories [15]. Table 5 shows the default CO_2 emissions factor as reported in [15]. To determine the CO_2 emissions for ground transportation (t CO_2) the following equation is used:

$$CO_{2transport} = \sum_{transport} C_{fuel} \cdot I_{fuel} \tag{1}$$

where

C_{fuel} represents the fuel consumed, (TJ) according to their type

I_{fuel} represents the emission factor (kg/TJ)

Table 6 shows the temporal trends of CO_2 emissions in Riyadh over the years. While these results do not capture the whole urban system and its interaction with the environment, they,

Table 5: Road transportation default CO_2 emissions factors.

Fuel Type	Default (kg/TJ)
Motor Gasoline	69 300
Diesel Oil	74 100
Kerosene	71 900

(Source: IPCC, 2006.)

Table 6: Total CO_2 emissions of energy consumption (stationary & mobile).

	Unit	1986	1996	2005	2012
CO_2 from electricity	million tons	6.2	10.9	17.6	27
	tons per capita	4.5	3.6	4.3	4.8
CO_2 emission from transportation	million tons	1.8	5.2	11.2	14.4
	tons per capita	0.3	0.5	0.6	0.5

however, shed light on the importance of adopting more rigorous policies to curb the environmental impact of fuel consumption by switching from oil-dependent energy production towards renewable sources.

5 CONCLUSION

The study used an urban metabolism approach to analyse the temporal trends of energy consumption in Riyadh, Saudi Arabia. The aim was to use this approach as an accounting tool to estimate the energy consumption and analyse the associated impacts. Although, due to lack of data, it relies upon estimates of past activities and some assumptions it is useful to provide insight into understanding the impact of future development.

The results highlighted the need to increase access to public transportation within the city boundaries. For this reason, the Arriyadh Development Authority (ADA) has initiated the planning and conceptual design stage for a Riyadh Public Transport system. This project is designed to form the backbone of the public transport system in Riyadh, and is scheduled for completion in 2018. The preliminary results also highlighted the importance of developing effective policies to improve the utilization of resources. Over the next 15 years, Riyadh is expected to become the first mega-city in the region. Further research is required to better understand the relationship between, and the impact of, urban flows and social and economic indicators.

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